Experimental analysis and predictive simulation of heat transport using TASK3D code

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Introduction I

- TASK3D [*] is an integrated transport code for helical plasmas and has been developed in collaboration between Kyoto Univ. and NIFS.
  

- We have developed and incorporated into TASK3D:
  - neoclassical transport database module, DGN/LHD
  - radial electric field calculation module, ER.

- In order to simulate the NBI heated plasmas, FIT3D[**] code are incorporated into TASK3D.


We can perform:

  » self-consistent calculation of the heat transport and the distribution of heating power of the experimental plasmas (Experimental analysis).
  » predictive simulations assuming a variety of NBI heating conditions (Predictive analysis).

- Using the improved TASK3D, heat transport simulations with several turbulent transport models have been performed to study LHD plasmas. ISHW(2009), IAEA(2010)
In order to improve the accuracy of the turbulent transport model in TASK3D, we have made the comparison and the validation with LHD experimental results (14th, Sep. 2011, EXP No. #773).

- Determination of more appropriate value for Constant Factor, $C_{\text{model}}$.
- Validation of the turbulent transport model (gyro-Bohm, Bohm, and Alcator model).
- Introduction of the extended gyro-Bohm model which is included the temperature gradient factor.


- Heat transport simulation in the time developing LHD plasmas
  A. Sakai (Kyoto Univ.), ITC22

- NBI heating analysis of time development plasma in LHD
  Yamaguchi(Kyoto Univ.), ITC22
Module Structure of TASK3D

- Each module, as shown here, describes different physical phenomena.
- Through the data exchange interface, each module is connected, and we can describe plasmas self-consistently.
1D (radial) diffusive transport eq.
- particle transport eq.
- heat transport eq.
- magnetic field diffusion eq.

The power deposition are calculated in response to change in spatial distribution of temperature and density in TR module.
Heat Transport equation: TASK/TR

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n_s T_s \right) = - \frac{1}{V'} \frac{\partial}{\partial \rho} \left( V' \left< \nabla \rho \right> n_s T_s \left( V_{K_s} + \frac{3}{2} V_s \right) - V' \left< \nabla \rho \right> \left( \frac{3}{2} D_s T_s \frac{\partial n_s}{\partial \rho} + n_s \chi_s \frac{\partial T_s}{\partial \rho} \right) \right) + P_s
\]

\( D_s \): the particle diffusion coefficient
\( \chi_s \): the thermal diffusion coefficient
\( V_s \): the particle pinch velocity
\( V_{K_s} \): the heat pinch velocity

We assume that the transport coefficients are given as the sum of a neoclassical term and a turbulent term.

And we also assume the turbulent term of the electron and the ion are equal.

\[
D_s = D_s^{NC} + D_s^{TB}, \quad s = s^{NC} + s^{TB}, \quad V_s = V_s^{NC} + V_s^{TB}, \quad V_{K_s} = V_{K_s}^{NC} + V_{K_s}^{TB}
\]

NC, neoclassical transport coefficient: neoclassical transport database, DGN/LHD.
TB, turbulent transport coefficient: the turbulent transport models.

In this study, we consider the turbulent term is only \( \chi^{TB} \). \( D_s^{TB} = V_s^{TB} = V_{K_s}^{TB} = 0 \).

<table>
<thead>
<tr>
<th>Bohm model emphasized on the edge region</th>
<th>gyro-Bohm model</th>
<th>Alcator Scaling model</th>
<th>advanced gyro-Bohm model (Including the effect of grad T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^{TB} )</td>
<td>( C_{edgeBohm} ) ( T ) ( r \frac{2}{a} )</td>
<td>( C_{gyroBohm} ) ( \frac{T}{eB} ) ( \frac{L}{a} )</td>
<td>( C_e^{(0)} ) ( \frac{1}{16} ) ( \frac{T_e}{eB} ) ( \frac{i}{a} ) + ( C_e^{(1.5)} ) ( \frac{1}{16} ) ( \frac{T_i}{eB} ) ( \frac{i}{a} ) ( \left( \frac{\nabla T_i}{T_i} \right)^3 )</td>
</tr>
</tbody>
</table>

In each model, the \( C_{model} \) is a constant factor.
## Reference Plasmas

The 15 cycle exp. (EXP No. #773, 14 SEP 2011)

<table>
<thead>
<tr>
<th>Shot num.</th>
<th>time [sec]</th>
<th>Rax [m]</th>
<th>$B_0$ [T]</th>
<th>$T_{e0}$ [keV]</th>
<th>$T_{i0}$ [keV]</th>
<th>$n_0$ [10$^{19}$ m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>109081</td>
<td>4.24</td>
<td>3.60</td>
<td>2.75</td>
<td>3.0</td>
<td>3.0</td>
<td>3.07</td>
</tr>
<tr>
<td>109082</td>
<td>4.24</td>
<td>3.60</td>
<td>2.75</td>
<td>3.2</td>
<td>3.5</td>
<td>2.78</td>
</tr>
<tr>
<td>109125</td>
<td>4.24</td>
<td>3.60</td>
<td>2.85</td>
<td>3.4</td>
<td>4.1</td>
<td>1.81</td>
</tr>
<tr>
<td>109129</td>
<td>4.24</td>
<td>3.60</td>
<td>2.85</td>
<td>3.4</td>
<td>3.8</td>
<td>2.63</td>
</tr>
<tr>
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<td>4.24</td>
<td>3.60</td>
<td>2.85</td>
<td>3.4</td>
<td>4.0</td>
<td>2.27</td>
</tr>
<tr>
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<td>3.60</td>
<td>2.85</td>
<td>3.4</td>
<td>3.8</td>
<td>2.61</td>
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<tr>
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<td>3.60</td>
<td>2.85</td>
<td>3.3</td>
<td>3.5</td>
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<td>3.60</td>
<td>2.85</td>
<td>3.3</td>
<td>3.4</td>
<td>2.99</td>
</tr>
</tbody>
</table>
The factor $C_{\text{model}}$ are determined so as to minimize RMS values.
- We show the results in the case of assuming the gyro-Bohm model.
Calculating the RMS values with the various values of $C_{\text{model}}$ in reference shots, the $C_{\text{model}}$ values which minimize the RMS are distributed from 22 to 27.
- We decide the $C_{\text{model}}$ value to 25 to minimize the summation of these RMS values.
- In this case, the averaged error between the experimental results and TASK3d results are about 20%.
Heat Transport Analysis using TASK3D

s88343: 1.833sec, $R_{ax} = 3.6m$, $B_0 = 2.75T$, $\beta_0 = 0.11$

**The ratio between the turbulent and the neoclassical transport coefficient is:**

- electron: factor $10$
- ion: factor $0.5\,\,1$

It is found that: [*]

the anomalous transport dominates in the electron thermal transport and
the neoclassical transport plays an important role in the ion thermal transport.

[*]A. Wakasa, et al., IAEA2010
Predictive Simulation Results of NBI Heated Plasma

We applied TASK3D to predictive heat transport simulations for the LHD experiment with $R_{\text{axis}}=3.6\text{m}$ and $B_0=-2.85\text{T}$. In this simulation, we assume the turbulent transport model as per the gyro-Bohm model with $C_{\text{gyro-Bohm}}=25.0$.

Each NBI power of port through is considered as: 
#1(5.8MW), #2(4.5MW), #3(4.5MW), #4(4.5MW), and #5(6MW).

We calculate the NBI power deposition along with the time evolution of electron and ion temperatures until the steady state.
Results of the Predictive Simulation of NBI Heated Plasmas

To validate the simulation results, the LHD experiments in the similar NBI heating condition and density profiles were performed (below).

The electron temperatures obtained by the predictive simulation are in good agreement with the experimental results ($T_e(r/a=0) \approx 3.2$keV and parabolic profile), and the ion temperatures in the experiment are about 25% higher than the predictive simulation results in the core region.
Comparison between Simulation and Experimental Results

gyro-Bohm model

\[ T_B^e = \frac{T_B^i}{c} \]

is assumed.

**TASK3D RESULTS**

Comparison between Simulation and Experimental Results

**EXP. RESULTS**

\[ \frac{\text{TB, EXP}}{nT_s'} = \frac{q_{PB}}{nT_s'} \]

Core:

\[ T_i^{\text{TASK3D}} < T_i^{\text{EXP}} \]

Edge:

\[ T_i^{\text{TASK3D}} > T_i^{\text{EXP}} \]

\[ \chi_e^{\text{TASk3D}} \text{ agrees with } \chi_e^{\text{TB,EXP}}. \]

\[ \chi_i^{\text{TASk3D}} \text{ disagrees with } \chi_i^{\text{TB,EXP}}. \]

\[ \chi_e^{\text{TB}} \text{ and } \chi_i^{\text{TB}} \text{ is not equal}. \]
Interrelation between gradient $T_i$ and $c_i$

Suppose the thermal diffusivity is proportional to the temperature gradient.

\[
\frac{\nabla T_i}{2} = 0 \quad \frac{\nabla T_i}{2} > 0 \quad \frac{\nabla T_i}{2} < 0
\]

\[
\frac{c_i}{r} = 0 \quad \frac{c_i}{r} > 0 \quad \frac{c_i}{r} < 0
\]

\[
\frac{i}{r} \mu \frac{\nabla^2 T_i}{2}
\]

We include the temperature gradient factor, $\alpha T'/T$, to the gyro-Bohm model as:

\[
\frac{T_{TB}}{i} = C_{\text{gyroBohm}} \text{grad}TgB \frac{T \alpha}{T}
\]
Gyro-Bohm Transport Models
Including the Effect of Temperature Gradient

We consider the effect of the temperature gradient on the heat transport and include the temperature gradient factor, aT'/T, in the gyro-Bohm model.

\[ T^B_i = C_i \ gB \ \frac{T}{T} \ \alpha \]

Here, \( m \) is the index to measure the effect of the \( \text{grad } T \) term in turbulence transport.

In the case of \( m=1.5 \), RMS value is minimized.

(using \( \text{grad } T \) to the 1.5th power is similar to the CDIM model [*])


not Including the Effect of Temperature Gradient

Including the Effect of Temperature Gradient

\[ e = C^{(0)}_e \ \frac{1}{16} \ \frac{T_e}{eB} \ \alpha + C^{(1.5)}_e \ \frac{1}{16} \ \frac{T_i}{eB} \ \alpha \left( \frac{\nabla T_i}{T_i} \right)^{\frac{3}{2}} \]

\[ i = C^{(1.5)}_i \ \frac{1}{16} \ \frac{T_i}{eB} \ \alpha \left( \frac{\nabla T_i}{T_i} \right)^{\frac{3}{2}} \]

simple \( gB \)
\( gB \times \text{grad } T_i \)
\( gB \times \text{grad } T_i \)
Simulation Results Using the Gyro-Bohm Models Including the Effect of Temperature Gradient

\[ \frac{\mathcal{T}_{i, \text{EXP}}}{\mathcal{T}_{e, \text{EXP}}} = \frac{q_s^{PB}}{nT_s^{NC}} \]

In the above equation, \( q_s^{PB} \) represents the power balance and \( nT_s^{NC} \) represents the density times temperature. The graphs illustrate the comparison of experimental data (EXP) with theoretical models (TASK3D) for various parameters such as ion temperature, electron temperature, density, and power input (\( P_i \)). The plots show how these parameters vary with the radius-to-aspect ratio (r/a) in different scenarios, highlighting the impact of temperature gradient on plasma behavior.
Heat transport simulation in the time developing LHD plasmas[*]

We perform the predictive simulations assuming the time evolution of the density.

- The density is increased up to 10 times during the 250 msec.

[*]A. Sakai, et al. ITC22, Toki, Nov. 20, 2012 [P2-16]
Summary I

• TASK3D is an integrated transport code for helical plasmas and has been developed in collaboration between Kyoto Univ. and NIFS.
  – We have developed and incorporated into TASK3D:
    » neoclassical transport database, DGN/LHD\(^{[1-2]}\)
    » radial electric field calculation module, ER
    » NBI heating power calculation code, FIT3D
  – Using the TASK3D, we have performed \(^{[4-5]}\):
    » self-consistent calculation of the heat transport and the distribution of heating power of the experimental plasmas (Experimental analysis).
    » predictive simulations assuming a variety of NBI heating conditions (Predictive analysis).
• Heat transport simulations with several turbulent transport models have been performed to study LHD plasmas \(^{[3,4]}\).
  » The turbulent transport dominates in electron thermal transport.
  » The neoclassical transport plays an important role in the ion thermal transport.
In order to reproduce the ion temperature distribution, we consider the improvement of the gyro-Bohm model\(^7\).

- We include the temperature gradient factor, \(aT'/T\), in the gyro-Bohm model.

\[
e = C_e^{(0)} \frac{1}{16} \frac{T_e}{eB} a + C_e^{(1.5)} \frac{1}{16} \frac{T_i}{eB} a \left( \frac{\nabla T_i}{T_i} a \right)^{\frac{3}{2}}
\]

- By including the effect of \(\nabla T\), TASK3D simulation reproduces both the electron and ion temperatures for LHD plasmas.

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